ARMY RESEARCH LABORATORY

Motion Sickness Literature Search

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Abstract

A review of the literature about motion-induced cognitive and perceptual decrements and about motion sickness was conducted to identify screening methods and mitigation techniques and to gain estimates of the portion of population affected. Screening and mitigation techniques that show promise for indirect driving will be evaluated in imminent laboratory and field experiments.

Contents

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1. Background

Motion sickness is a syndrome precipitated by different forms of travel, amusement park rides, and other unusual forms of motion. There are generally three classes of symptoms that can be distinguished. The first class consists of a disruption in perceptual and sensorimotor activities involving the vestibular system, such as disorientation, disequilibrium, and inappropriate vestibulo-ocular or vestibulo-spinal reflexes. The second group also appears to have a perceptual origin and consists of many autonomic symptoms such as pallor, drowsiness, salivation, sweating, nausea, and vomiting. The third set of symptoms is referred to as the "sopite syndrome" which includes symptoms such as mood changes, lethargy, and sleep. The onset of motion sickness symptoms is known to cause performance decrements (Yardley, 1992; Lawson & Mead, 1998).

To equip the Army with a rapidly deployable force, combat vehicles need to be smaller, lighter, survivable, and more mobile. Future combat vehicles require crew stations to be positioned deep within the vehicle hull. Vision blocks and sights will be replaced with cameras and displays. Thus, driving will be conducted with indirect vision that can lead to motion sickness because of display resolution, field of view (FOV), and system lag problems. In addition, vehicle control will be exercised through controls and displays without a direct view of the outside world. Because the Future Combat Systems program emphasizes moving operations, any additional perceptual and cognitive load placed on the soldier may result in unacceptable performance decrements. As a result, the Human Research and Engineering Directorate of the U.S. Army Research Laboratory (ARL) has identified a need to investigate and identify the causal effects of motion sickness as related to indirect driving and the use of displays in combat vehicles. In preparation for experimental research, ARL completed a literature search to investigate possible prevention methods, the percentage of population affected, and possible subject screening methods. The results yielded the identification of susceptibility factors, motion sickness theories, and motion sickness history questionnaires that may be used for validation purposes and may provide a means to screen study participants. No research was conducted on motion sickness associated with indirect driving. Factors influencing susceptibility include sex, age, exposure history, receptivity, adaptability, and personality characteristics. ARL's research will be tailored to validate screening methods and to apply previous successful efforts in reducing motion sickness to current systems and development.

2. Findings

2.1 General

2.1.1 Reason, 1978

Reason reviewed some important theoretical and practical considerations related to motion sickness. Sensory rearrangement theory is briefly outlined. Behavioral measures to minimize the risk of motion sickness, quantitative studies of vertical periodic motion, factors influencing susceptibility to motion sickness (sex, age, exposure history, receptivity and adaptability, and personality characteristics), and recommendations of the most effective use of anti-motion sickness drugs are discussed. Based on previous research, a variety of drugs and drug combinations was shown to offer some protection against motion sickness, but none are entirely effective in all conditions.

2.1.1.1 Sensory Rearrangement

Sensory rearrangement, a predominant theory, was coined to describe the main ingredient of experimental situations in which information reaching one set of receptors is systematically distorted to render it incompatible with that reaching functionally related receptors. The spatial senses (eyes, vestibular system, proprioceptive receptors in joints, tendons, and muscles) function in harmony to convey perfectly correlated information. This delicate harmony can be disrupted when persons work in an environment where these senses conflict. When we allow ourselves to be transported by mobile device or to be moved within an unusual force environment, this delicate harmony is disrupted. Incongruity among the normal channels of information is produced and a mismatch occurs between the pattern of spatial input of what is perceived and what is expected, based on previous experience with the natural environment. Two classes of sensory rearrangement include visual-inertia rearrangement (inertial includes both the vestibular and non-vestibular proprioceptors) and canal-otolith rearrangements (when vision is absent). The synergistic relationship between visual and inertial senses and between the canal and otolith receptors can be disturbed in three ways[1].

Type 1 - When A and B simultaneously signal contradictory or uncorrelated information.

Type 2 - When A responds in the absence of an expected corroborating signal from B.

[1] Note. A and B represent positions of these normally correlated receptor systems; specifically, A represents visual or canal while B represents inertial or otolith, respectively.

Type 3 - When B responds in the absence of an expected corroborating signal from A.

Therefore, six situations in which motion sickness may be expected to occur if the theory is true can be derived from the two classes of sensory rearrangement and three conflict types (see Table 1).

Table 1. Sensory Rearrangements Known to Produce Motion Sickness

	Type of motion cue mismatch Visual (A) - Inertial (B)	Canal (A) - Otolith (B)
Type I: A and B simultaneously signal contradictory information	1. Seated so that the external view is from a side or rear window of a moving vehicle	1. Tilting the head about an axis other than the axis of spinning while riding on a rotating platform (cross-coupled or Coriolis sickness).
	2. Moving the head while wearing an optical device that distorts the visual field.	2. Making quick head movements while in weightless flight (space sickness).
Type II: A responds without expected B signal	1. Viewing a cinerama-type motion picture while in a moving vehicle.	1. Irrigating the outer ear with water that is hotter or colder than blood temperature (caloric stimulation).
	2. Operating a fixed base vehicle simulator with a dynamic visual display (simulator sickness).	2. Pressure vertigo because of ambient pressure changes.
Type III: B responds without expected A signal	1. Trying to read a map or book while in a moving vehicle.	1. Low frequency (<0.5 Hz) linear oscillation.
	2. Riding in an enclosed vehicle (no external visual reference).	2. Rotation about a non-vertical or earth-horizontal axis.

There are at least two important implications for the practical management of motion sickness. First, the applied researcher is directed to assess the nauseogenic potential of a particular vehicle design or seating configuration. The sources of motion information available to the passenger and how these sources are most likely to be in conflict need to be determined. The researcher then needs to consider whether an existing conflict could be eliminated or reduced by repositioning the passengers' seats or providing a more adequate external visual reference.

When possible, seats should be designed to give positive head restraint, since limiting independent head wobbling is known to be highly effective in reducing the incidence of motion sickness. There is also considerable evidence that adopting the supine position (lying on the back with face upward) reduces the risk of symptoms. Second, the passenger has considerable behavioral control over his or her own susceptibility. Canal-otolith conflicts can be minimized by keeping the head as still as possible or by adopting the supine position when practical. Visual-inertial conflicts can be minimized by maintaining a clear view of the road ahead, focusing on the horizon or on any visible landfall. When a visual-inertial conflict is inevitable (e.g., when sitting in a backward or sideways facing seat or being below decks or in any enclosed vehicle), it often helps to close the eyes. If this is impractical, some benefit may be gained by wearing an optical device that occludes the peripheral visual field, leaving the central area unobscured. Thick spectacle frames may even confer some advantage. There is considerable evidence that the central FOV is minimally involved in maintaining spatial orientation.

2.1.1.2 Quantitative Studies of Vertical Periodic Motion

Wave frequency is the critical factor in triggering mechanisms responsible for motion sickness in vertical periodic motion, and the greatest responsivity of these mechanisms is the frequency region of 0.2 Hz. Sickness incidence diminishes with increasing frequency and is nearly nonexistent above 0.6 Hz. Sickness incidence increases as a monotonic function of acceleration level over a range from 0.03 g to 0.04 g. As a result, caution has been given against the engineering strategy of "smoothing" the ride characteristics by reducing the high-frequency motion (over 0.5 Hz) at the expense of increasing energy in the lower frequency bands, since even moderate accelerations at frequencies in the region of 0.2 Hz produce a very high risk of motion sickness.

2.1.1.3 Motion Sickness Susceptibility Factors

Factors influencing susceptibility include sex (women are more susceptible than men), age (peaks at age 12, then declines), exposure history (experiential factors may contribute to gradual diminution of susceptibility), receptivity (refers to the characteristic way the central nervous system transduces or codes stimulus energy), adaptability (refers to the rate at which an individual adjusts to sensory rearrangement), and personality characteristics (positive correlation between neuroticism and motion sickness susceptibility; susceptible persons tended to have a more emotional or autonomic nervous system response to stress).

2.1.2 Brand and Reason, 1975

Brand and Reason discuss the weaknesses of the over-stimulation and otolith theories while supporting the "sensory conflict" theory and the neural mismatch hypothesis of motion sickness. The central thesis is that the conflict theory offers the most plausible basis for the identification of essential common features of

different situations that provoke symptoms. All motion sickness-provoking situations involve sensory rearrangement whereby motion signals transmitted by the eyes, vestibular system, and nonvestibular proprioceptors are mismatched with one another as well as what is expected because of prior experience. The vestibular receptors are always implicated directly or indirectly in these conflicts as in visually induced sickness. The input to the vestibular receptors is artificially distorted, rendering them incompatible with the eyes, one another, or both.

Most sickness-provoking sensory conflicts fall under two general headings. One is visual-inertial rearrangements in which the conflict lies between two sense modalities[2], and the other is canal-otolith rearrangements in which the conflict is within one modality, between the two vestibular receptor systems.

When an individual is denied an external visual reference (such as passive vehicular motion in which the passenger does not have a clear view of the external environment), motion sickness susceptibility may be reduced by the passenger shutting his eyes or having an artificial horizon provided.

Brand and Reason also discuss "protective adaptation," which is a diminishing and eventual disappearance of motion sickness signs and symptoms in most individuals after prolonged exposure to a provocative stimulus.

Motion sickness most likely first appeared as a result of man's first attempt to improve his mobility through the construction of a boat.

In 1881, Irwin remarked that seasickness was prompted by a "discord between the immediate or true visual impressions and a certain visual habit or visual sense of the fitness or order of things..." This was coined the "visual vertigo" theory, which is similar to sensory conflict.

Motion sickness was a problem of "considerable military significance" during World War II. Motion sickness resulted in serious efficiency degradation because troops were not accustomed to being transported by land, sea, and air.

Wave motion research directed by Wendt at the Wesleyan University and University of Rochester revealed that sickness incidence peaked in a frequency range between 0.25 and 0.33 Hz.

Brand and Reason discuss the fact that similar findings by investigators using swings with a frequency swing of 0.25 Hz were effective in producing sickness. Faster or slower swinging rates resulted in lower incidence of sickness.

[2]In which "inertial" refers to both the vestibular and nonvestibular proprioceptors

Benson (1973) obtained a clear negative correlation between sickness incidence and the frequency of oscillation over a range of frequencies investigated (0.22 to 0.59 Hz).

The consistent finding in vertical oscillation studies is that 0.25 Hz is most effective in producing sickness, while frequencies of 0.55 Hz or greater generally elicit little or no sickness. Experimental evidence shows that within a frequency range of 0.1 to 1.0 Hz, there is a change in phase angle between the stimulus and the response from otolithically driven cells in the vestibular nuclei, while between 1.0 and 2.0 Hz, the phase angle is relatively stable.

In 1942, the National Research Council of Canada studied the cause, incidence, and control of motion sickness. Canadian wartime investigators made some of the most significant contributions toward motion sickness prevention and understanding. The "roll-pitch rocker" was used in these studies to simulate vehicle motion (Morton et al., 1947). Later, the two- and four-pole swings became the primary research tools (Manning, 1943; Manning & Stewart, 1949). Johnson and his colleagues demonstrated that mechanical head restraint is effective in reducing the incidence of sickness aboard various types of transport. Canadian researchers also conducted drug studies. The principal result was the Royal Canadian Navy seasickness remedy—a combination of hyoscyamine, hyoscine, and niacin. The United States armed services later adopted this preventive medication.

Russian investigators exposed their trainee aviators to vestibular training (a full gamut of accelerative stimuli before flight). It was designed to prevent motion sickness by promoting "statokinetic stability." This reflects a person's ability to regain balance after being subjected to rapid rotation that artificially disturbs the sense of orientation.

The most important wartime discoveries included understanding the functioning of the vestibular system in producing symptoms, the efficacy of hyoscine as a preventive, susceptibility assessment techniques, protective adaptation mechanisms, quantitative data about effective characteristics of motion stimulus, and important qualitative information about the effects of head position and external visual reference on motion sickness susceptibility.

Brand and Reason further discuss three types of conflict within each of the two broad rearrangement categories. There are six distinct kinds of sensory conflict in which motion sickness can occur.

Graybiel (1965) concluded that motion sickness is a "vestibular sickness" after 10 years of study of individuals whose labyrinths had been destroyed. These

individuals never experienced motion sickness symptoms during exposure to a wide variety of provocative situations.

There are few investigators today who would claim that the semicircular canals are exclusively involved in the cause of motion sickness. The same holds true for the "otolith-only" viewpoint.

The supine position is beneficial in reducing motion sickness symptoms and can be attributed to the otoliths being less responsive to vertically acting linear accelerations. The supine position offers a considerable degree of head restraint.

Brand and Reason discuss motion sickness and performance, motion sickness susceptibility factors, Coriolis techniques, and questionnaires to reveal an individual's sickness frequency and severity of symptoms.

2.1.3 Yardley, 1992

This research examined the role of activity and perceptual learning in motion sickness through a survey of two kinds of research. The first is concerned with perception of orientation and self-motion during the conditions of "sensory conflict," which are thought to cause motion sickness. The second consists of investigations into prediction and prevention of motion sickness. The inconclusive results of both kinds of motion sickness research have stemmed from a common neglect to examine the role played by active perceptual strategies, exploration, and voluntary movement in reactions to unusual perceptual environments. The studies reviewed in this paper have used unrepresentative perceptual conditions and have controlled or ignored the voluntary activities and perceptual strategies employed by their subjects. Therefore, these studies have excluded the very factors most likely to influence responses to nauseogenic conditions. A complete re-evaluation of motion sickness seems overdue. It is suggested that research addressing susceptibility and resistance to environments provoking illness adopt a fresh approach. More specifically, research should be concerned with informative structures that can only be defined in relation to the activities of the perceiver.

2.2 Visually Induced

2.2.1 Dolezal, Connon, and O'Neal, 1985

In this study with 15 subjects, the visual environment was manipulated by prismatically reversing the "up-down" FOV, which was preceded by a no-prism baseline condition. The purpose of this procedure was to determine if unfamiliar and unexpected optical information can lead to motion sickness. Vestibular stimulation was held constant. Subjects were required to repeat six visually guided fine motor coordination tasks that followed an increasing order of difficulty for all subjects. The first three tasks were standardized Bailey Infant Scale of Mental Development Items. First, subjects were asked to drop 10 small

1/2-inch cubes singly into a small hole in the center of a container after removing the top, emptying the cubes, and replacing the top. Second, subjects were asked to remove six pegs from a pegboard, place the pegs on the side of the pegboard farthest from him, and to replace them. Third, subjects were asked to build a tower of eight, 1-1/4-inch cubes from a pool of 12 cubes symmetrically arranged in a 5-inch by 6-1/2-inch by 2-1/2-inch deep box. Subjects had to place the eight blocks on the table first before they began building the tower. Fourth, subjects were required to exchange one AA size battery in a 4-1/2-inch by 2-1/2-inch calculator for another. Fifth, subjects were shown a standard 13-inch by 13-inch checker board fully set up for play and were asked to replace the plastic pieces exactly. The experimenter then placed the game pieces by handful into a 5-1/4-inch by 6-3/4-inch by 2-1/2-inch deep box from which the subjects were required to retrieve them. Sixth, subjects were asked to place, from a tray, 2-1/2-inch long plastic pegs into their respective holes in a "Score 4," 8-inch by 8-inch game board and then to place one plastic bead on each of the pegs. Times were recorded. Additionally, behavioral tests were conducted, which included perceptual tasks, equilibrium tests, fine and gross motor coordination tests, and motion sickness ratings. The short session was 65 to 75 minutes, and the long session was 85 to 100 minutes.

The following symptoms were observed: dizziness and queasiness, especially during head movements; poor balance when participants stood; unsteady equilibrium while participants walked; disorientation when participants moved around and during attempted precise eye-hand coordination; and associated autonomic activity including sweating (GSR), muscle tension (EMG), skin surface temperature (EDG), and pulse throughout.

Subjects showed rapid improvement when they performed six visually guided fine motor coordination tasks for a second time. The results demonstrated the prominent role played by unfamiliar and unexpected optical movement information. This experimental paradigm is believed to perceptually pre-adapt personnel to the ill effects visually inherent in disorienting situations.

2.2.2 Dobie, May, Fisher, and Bologna, 1989

Techniques for reducing visually induced motion sickness were examined. Subjects were selected and assigned to one of four groups, based on their responses to a motion sickness questionnaire. One group received 10 sessions of desensitization training (DT) only; a second group received 10 sessions of cognitive therapy (CT) only; a third group received 10 sessions of combined desensitization and cognitive therapy treatment (CG); and a fourth group received no treatment (C). The results indicated that the groups that received cognitive therapy (i.e., CT and CG) exhibited significant increases in tolerance to visually induced motion (VM) when pre-treatment measures were compared to post-treatment measures.

2.2.3 Dobie and May, 1990

The objective was to determine to what extent training tolerance of one motion stimulus would generalize other motion experiences. The three apparati used included a Dichgans and Brandt circular drum with a mirrored ceiling and inner surface lined with 6-inch wide alternating black and white vertical stripes, a rotating chair that tilted ±40° in both the frontal and lateral planes, and a standard video monitor that displayed a white square that expanded from 1° to 9° of visual angle over repeated periods of 800 ms. During post-tests, it was revealed that treatments with the chair and the drum provided specific increases in tolerance of the device used during treatment and that treatment with the chair provided a generalized tolerance of visually induced motion. The results supported the notion of specific and general components in learning to tolerate motion environments.

2.2.4 Tiande and Jingshen, 1991

Findings show that yaw vection, combined with pitch or roll head movements, significantly increased motion sickness, while pitch vection with any type of head movement or head and scene rotation about the same axis significantly reduced motion sickness. When the head was kept stationary, pitch vection was most stressful for motion sickness, followed by roll vection, then yaw vection, although yaw vection was the strongest sensation of self-rotation.

2.3 Coriolis Induced

2.3.1 Woodman and Griffin, 1997

Coriolis stimulation (or cross-coupled stimulation) occurs when the head is rotated about an axis other than the axis of rotation of the body. This will occur, for example, when the head is rotated in pitch while the person sits on a chair and undergoes continuous rotation in yaw (i.e., about a vertical axis).

Coriolis stimulation studies are often conducted with constant speed rotation about an axis close to the head. However, head movement required to cause cross-coupled stimulation tends to take the head away from the center of rotation. At positions other than at the center of rotation, the head will be exposed to gravitational acceleration as well as centripetal acceleration. Therefore, when the head moves, the change in acceleration differs from the acceleration that occurs with the same head movement at the center of rotation. The otoliths will give a response to head pitch through the acceleration caused by the combination of the earth's gravitational field and any centripetal acceleration. If otolith signals influence motion sickness during Coriolis stimulation, a difference in sickness can be expected when head movements are made at the center of rotation (where there is no centripetal acceleration) or away from the center of rotation.

One objective of this experiment was to compare sickness provoked by Coriolis stimulation when the person is seated away from the center of rotation with sickness when the person is seated at the center of rotation.

There were 24 blindfolded participants who were trained to make 30-degree pitch motions of the head every 30 seconds while rotating about a vertical axis at 10 rpm on a turntable at two separate locations: (a) at the center of rotation, and (b) 0.75 m from the center of rotation. Following each head movement, the participants rated their motion sickness. The reported symptoms varied between participants from simply becoming tired to slight dizziness to very nauseous.

It was concluded that precise body location at the center of rotation is not critical during Coriolis stimulation, but the direction of head movement has a large effect on nausea. Participants responded that rotating the head downward (i.e., pitched forward) gave rise to increased motion sickness symptoms more so than did rotating the head upward. It is suggested that there is an influence of somatosensory information on sickness caused by Coriolis stimulation. There were no significant differences between the ratings given by men and women either at the center of rotation or at the radius of rotation.

2.3.2 Cowings and Toscano, 1982; Toscano and Cowings, 1982

Autogenic feedback training (AFT) for motion sickness symptom suppression was the focus of Cowings and Toscano's (1982) research. Twenty-four men were randomly assigned to four groups matched for Coriolis motion sickness susceptibility. Coriolis sickness involves cross-coupled angular acceleration whereby the head is rotated about an axis other than the axis of bodily rotation. These head motions deliver Coriolis accelerative stimulus to the semicircular canals which then give signals that differ from those that occur with this head movement in a stationary environment. The "unexpected" signal from the semicircular canals offers a varied combination of canal, otolith, and somatosensory signals than what is expected from past experience. This is one cause of motion sickness.

Treatment group I (highly susceptible) and treatment group II (moderately susceptible) significantly improved performance in the Coriolis sickness susceptibility index (CSSI) after being taught to control autonomic responses with a training method called autogenic feedback. The highly and moderately susceptible groups were given 2 hours of this training about self-regulation of physiological responses. The article discusses receptivity, a perceptual phenomenon that describes how the central nervous system as a whole codes stimulus intensity. It is believed that a neural mismatch produces a stress-like response of the autonomic nervous system. Delineation between the tonic and phasic properties of a specific biological process (e.g., heart rate) is necessary since these physiological responses are time dependent. Tonic activity is the underlying baseline level that is more stable over a longer period of time. Phasic

activity is the responses superimposed on the tonic level, which are more unstable and of shorter duration. Tonic and phasic properties of a specific biological process (e.g., heart rate) are also discussed. AFT is an autonomic conditioning procedure. Frequent observations of individuals who are highly susceptible to motion sickness initially produce larger shifts from baseline in autonomic response levels as a consequence of nauseogenic stimulation, whereas individuals of moderate or low susceptibility exhibited more tightly integrated patterns of activity with changes of smaller magnitude. As an individual learns to diminish autonomic reactivity, the tolerance of motion-sickness-eliciting stimuli increases. It is possible that observed differences in initial susceptibility may be related to the ability of the brain to effectively regulate autonomic reactions to nauseogenic stimuli.

Toscano and Cowings (1982) compared AFT and an alternate cognitive task at reducing motion sickness. AFT involved practicing a series of mental exercises to facilitate control of autonomic activity which, in turn, reduced the tendency for autonomic activity levels to diverge from baseline during stressful conditions that cause motion sickness. The alternate cognitive task involved a probability-monitoring task in which subjects played "blackjack" with verbal information only. Visual and verbal information was provided until the subject could play blackjack with verbal information only. The subject's cards were read to him between head movement instructions. Each subject was asked to keep track of the game, emit verbal responses for "playing the hand," and make head movements as requested via a tape-recorded voice.

Eighteen men were randomly assigned to three groups matched for Coriolis motion sickness susceptibility. Group I was taught to control their autonomic responses. Group II received "sham" training and an alternate cognitive task, and Group III received no treatment. The treatment group received a total of 6 hours of autogenic feedback training in self-regulation of physiological responses. Results showed that Group I could withstand the stress of Coriolis acceleration as much as three times longer after training. There were no changes in Groups II and III.

2.3.3 Miller and Graybiel, 1970

A standard method for quantifying susceptibility to Coriolis sickness was evaluated. The subject was secured in a Stille rotary chair and blindfolded to eliminate any visual influences. Each subject was required to demonstrate the standardized head movement sequence that provides the Coriolis acceleration during chair rotation. The chair was accelerated in a clockwise or counterclockwise direction until one of several constant velocities was reached. Sequential head movements were continued until a cumulative point score of symptoms totaled 8, the lowest number of points in the severe malaise criterion (M III). Motion sickness signs and symptoms were scored on a tally sheet. When head movements at a constant chair velocity produce vestibular stress that

exceeds functional vestibular reserve, the average relative stimulus effect of a single head movement can be expressed by factor E. Factor E is linearly related (log/log function) to chair velocity. The CSSI, each individual's score, can be calculated by multiplying the E factor for the revolutions per minute used in the study by the number of head movements (N) required to elicit M III (CSSI = E x N). The result yields a quantitative motion sickness susceptibility to Coriolis acceleration within a single scale of numbers (1 to 100).

2.4 Immersive Virtual Reality

2.4.1 E.C. Regan, NATO Research Study Group 16 Workshop Presentation

This study was conducted to document the frequency of occurrence and severity of negative or unwanted side effects of immersive virtual reality (VR) technology. Apparatus included a Provision 200 VR system, virtual research flight helmet, Polhemus Fastrak tracking system, three-dimensional (3-D) mouse, and standard demonstration software. Subjects were required to complete a malaise rating scale before the immersion, at 5-minute intervals during the 20-minute immersion period, and at 5 and 10 minutes post-immersion. Subjects also completed a standard simulator sickness questionnaire immediately before and after the immersion. The questionnaire consisted of a range of symptoms that invited the subjects to respond to the absence, presence, and (sometimes) severity of the symptoms. Sixty-one percent of subjects reported some symptoms of malaise at some point during the 20-minute immersion period and 10-minute post-immersion period. These symptoms ranged from headaches and eye strain to severe nausea. Five percent of the subjects had to withdraw because their symptoms were severe. Two possible side effects were documented and discussed. The first possible cause is a conflict of senses during VR immersion that results in malaise. The second is technology factors, such as display resolution, which are responsible for some of the symptoms.

Many of the side effects that result from VR immersion are similar to motion sickness symptoms. This article discusses sensory conflict theory and the fundamental signs and symptoms of motion sickness (nausea, pallor, flushing, cold sweating, abdominal discomfort, changes in gastric motility, changes in levels of circulating hormones, and cardiovascular and respiratory changes).

The basis of the *sensory conflict*, a prevalent theory, is that all conditions that provoke motion sickness are characterized by a situation in which the signals transmitted from the visual system, the vestibular system, and the non-vestibular position senses conflict with each other or with our expectations that are based on previous experience. There are two main conflict categories: either the information from the visual system and the information from the vestibular system are incompatible with each other, or the information from within the vestibular system is incompatible (i.e., canals and otoliths provide incompatible signals).

Immersive VR can induce sensory conflict when movement is controlled by some form of hand device. It induces a conflict with the visual and vestibular systems; the visual system suggests body movement while the vestibular suggests a more static body position. It would seem plausible that by bringing the visual and vestibular cues more into alignment, side effects would be reduced. One way might be to facilitate more natural methods of moving through virtual environments such as coupling subjects' movements on a treadmill to their movements in the virtual world or interfacing an exercise bike to the VR system. Sensory conflict is unlikely to be the sole causal factor. Some side effects may be attributable to technological factors such as resolution, FOV, and system lag. Low-resolution head-mounted displays (HMDs) are more likely to increase visual system stress than higher resolution devices. The impact of resolution improvements is not clear. It is suggested that visual enhancements may not reduce malaise. Some evidence even suggests increased simulator discomfort with technological advances. It is unclear what effect FOV has on malaise during VR immersion. A wide FOV may create more compelling feelings of vection that may increase malaise, but a narrow FOV may require greater head movements that may also increase malaise.

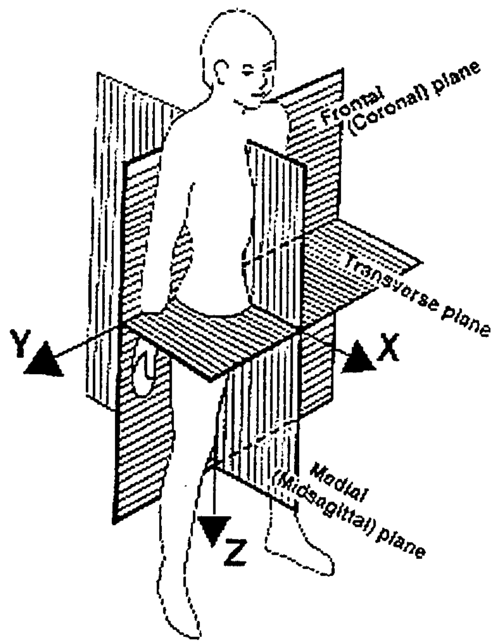
Literature about simulator sickness suggests that symptoms of malaise increase as system lag increases. Anecdotal evidence suggests that variations in lag, rather than lag by itself, cause malaise. Display update lags may induce a conflict when the time between an action (head movement) and the result (change in visual scene) become discernible. The visual-vestibular conflict arises from discrepancies in time between the physical movement (provides vestibular cues) and the movement of the visual field. Presently, there are few data about minimum discernible lags or acceptable levels of system lag.

2.5 Low Frequency Linear Oscillation

2.5.1 Golding and Kerguelen, 1992; Golding, Markey, and Stott, 1995

Golding and Kerguelen (1992) compared the nauseogenic potential of low frequency linear motion in the "earth-vertical" (sitting upright) versus the "earth-horizontal" (supine) plane, delivered through the same Z-axis of the head and body. Subjects were exposed to linear motion (0.3 Hz, 1.8 ms^{-2} root mean square) through the same head and body Z-axis in earth-vertical versus horizontal while they performed a continuous visual search task or shut their eyes. The visual search task required each participant to search for a number that was defined by the intersection of a letter (column) and number (row) combination. This combination was given to the participant verbally. The search matrix consisted of 12 columns by 12 rows. The defining letters (A to L) and numbers (1 to 12) were placed in a random order to make the participant scan widely. The matrix was situated 0.6 m from the participant's eyes. Analysis of covariance for sickness rating as covariant of performance, removing any time and subject, vertical or horizontal effects, revealed a small but significant

relationship between deviation in sickness rating and concurrent deviation in performance (r = -0.21, df 120, 2-tailed $p < 0.05$). There was correspondence to a reduction in response rate by approximately two responses per minute across the extremes of sickness rating from "feeling OK" to "moderate nausea". Results showed that vertical motion was clearly more provocative than horizontal motion. Performance of the search task was hampered by motion sickness.



Golding, Markey, and Stott (1995) demonstrated that low frequency linear oscillation through the z-axis of the body was more nauseogenic when it was applied in the vertical direction, with subjects seated upright, than in the horizontal direction, with subjects supine. Results suggest that upright versus supine body posture and stimulation through x-axis versus z-axis together enhance the nauseogenicity of low frequency linear oscillation, and these effects are additive. However, motion direction with respect to gravity vector (horizontal versus vertical) is a less important factor.

A servo-controlled hydraulic platform with a canvas cab that housed a seat and headrest produced vertical motion. A sled carrying a similar enclosed canvas cab that housed a seat and headrest produced horizontal motion. A standard five-point harness with quick release box was used to restrain subjects. A padded rear head support was provided. Otherwise, the head was not restrained. Subjects were enclosed in a canvas cab to eliminate visual and tactile (airflow) cues of motion. Subjects were required to perform a continuous visual search task according to verbal instruction that consisted of searching for a digit in a 12-by-12 matrix. This search task acted to control attention and augment nauseogenicity of motion.

In Experiment 1, subjects received two linear oscillatory motion changes: upright seated posture with horizontal motion through the x-axis of the head and body and upright seated posture with vertical motion through z-axis of head and body. The degree of motion sickness rating scale was 1 = no symptoms; 2 = mild symptoms, but no nausea; 3 = mild nausea and any additional symptoms; 4 = moderate nausea and any additional symptoms. The time to sickness ratings were significantly higher for horizontal than for vertical motion. Total symptom scores until motion stopped were significantly less for vertical than for horizontal.

There were three conditions in Experiment 2: upright seated with horizontal motion through x-body axis; upright seated posture with vertical motion through z-body axis; and supine posture with vertical motion through x-body axis. There were no significant analysis of variance effects for time to sickness rating 2. There was a significant effect of time to sickness rating 3 for motion condition for all subjects.

Through examination, means and specific comparisons revealed that time to reach sickness stages 3 and 4 was significantly less for horizontal than for vertical.

2.6 Simulator Sickness

2.6.1 Kennedy, Fowlkes, Berbaum, and Lilienthal, 1992

This paper discussed the usefulness of a motion sickness history questionnaire (MHQ) in the prediction of simulator sickness, a form of motion sickness experienced by individuals who train in ground-based flight simulators. Four MHQ scoring keys were compared. Navy and Marine Corps aviators (N = 456) completed the MHQ before their regular flight simulator training. All scoring keys were predictive of reported symptoms. The highest correlation was obtained with the simulator sickness (SS) key. Therefore, it was suggested that pilots use the SS key for self-testing so that they may be aware of their risk for simulator sickness. The use of this SS questionnaire may reduce safety risk, optimize training, and avoid flying restrictions imposed when symptoms are experienced.

2.7 Seasickness

2.7.1 Rolnick and Bles, 1989

The incidence of motion sickness in sailors working below deck is generally higher than in those who have the horizon as a visual reference on the bridge. This study looked at the possible benefit of a projected artificial horizon as a means of preventing seasickness. Twelve subjects were exposed to angular motion in a tilting room during three conditions: a) windows covered, allowing

no visual reference from the outside world; b) windows uncovered, allowing a partial view of the environment; and c) windows covered and a horizon projected onto the walls by a rotating laser beam. Subjects were exposed for 35 minutes in each condition while they performed different computerized tasks. There were fewer symptoms of motion sickness in the "artificial horizon" and "window" conditions. The presence of visual reference prevented the decrement in performance found in the "closed cabin" condition. These results suggest that a projected horizon may alleviate motion sickness aboard naval vessels and thus improve performance.

2.7.2 Wiker, Kennedy, McCauley, and Pepper, 1979

This study showed significant covariance between the magnitude of motion sickness symptomatology and the encounter direction of the vessel to primary swell. When the vessel was steaming into the seas or primary swell, motion sickness severity was greatest. Sea state, direction in which the vessel encountered the primary swell, and hull design played a major part in motion sickness provocation aboard marine vehicles.

2.8 Ground Vehicle Sickness

2.8.1 Rolnick and Lubow, 1991

Control was examined as a possible factor in motion sickness. It has been noted that being a driver instead of a passenger of a moving vehicle greatly reduces the likelihood of motion sickness just as pilots have been found to be less susceptible than other crew members. The purpose of this study was to empirically validate findings by Reason and Benson that motion sickness is not solely based on sensory information but on other influences such as the role of intention, feed-forward mechanism, or efferent-afferent correlation. Factors that have been suggested to explain driver immunity, including head movements, visual information, perceived control, predictability, and activity, are discussed. Twenty-two pairs of yoked subjects were exposed to nauseogenic rotation. Paired active and passive male subjects were placed in a two-seat rotating device. The active subject had a joystick with which he could control rotation. The passive subject was exposed to the same rotation without control. The heads of the subject pair were yoked by a rod attached to two helmets that were worn by the subjects. Only the active subject initiated head movements. The passive subject was asked to go along with the movements. Active (controllability) subjects were less likely to terminate before the experiment's completion, showed reduced motion sickness symptoms, and showed less decrement in their well-being, as compared to the passive subjects.

2.8.2 Vogel, Kohlhaas, and von Baumgarten, 1982

The purpose of this study was to test the hypothesis that otolith stimulation by linear acceleration in a car may elicit motion sickness. Thirty-eight healthy

subjects were accelerated in an ambulance car. Weak forward acceleration was alternated with brisk braking. Subjects were placed in one of the following positions: (1) sitting upright and facing forward in the car, (2) lying supine, head forward on a stretcher, (3) lying in a supine position, head backward. The experiment was terminated when 30 braking actions were completed or when the subject requested to stop. Motion sickness symptoms were observed and recorded after each trial via a scaling index that was weighted according to the strength of any particular symptom. The experiment clearly showed that horizontal linear acceleration in a car, coupled with the stop-and-go technique is effective in provoking motion sickness. More than 43% of the subjects became motion sick in less than 10 minutes.

2.8.3 Turner and Griffin, 1999

Turner and Griffin wanted to identify personal and environmental factors influencing individual susceptibility to motion sickness during road transport. A 14-item questionnaire was completed by 3,256 coach passengers pooled across 56 coach journeys. The questionnaire contained two measures of motion sickness, with a further item asking for information about sickness onset time. The first sickness measure, illness rating (IR), consisted of a 4-point subject rating of well-being. The second measure of motion sickness addressed specific symptoms. Passenger ages ranged from 8 to 80 years. Passenger characteristics, travel regularity, activity during travel, use of anti-motion sickness drugs, and self-reported motion sickness susceptibility were collected during the 56 coach journeys. Travel environment characteristics (visibility, temperature, and seating) were also recorded. The relationship of these variables to passenger illness and more specific motion sickness symptoms was examined. Overall, 28.4% of passengers reported feeling ill, 12.8% reported nausea, and 1.7% reported vomiting during travel coach. Sickness decreased with increasing age and travel experience. Females reported feeling ill more than their male counterparts by a ratio of four to three. Sickness was found to increase with poor forward visibility. Occurrence of illness was approximately three times higher for passengers with no view of the road ahead (mean, 34.6%) compared to those who could see the road ahead extremely well (mean, 12.7%). No relationships were found between the occurrence of sickness and temperature or time of travel. This research also suggests that habituation through greater travel regularity occurs independently of reductions that occur with age. Differences in the pattern of sickness responses exhibited by males and females suggest that females are more affected by a poor forward view. It is predicted that motion sickness in coaches may be reduced through improved saloon and window designs in order to maximize external passenger visibility.

2.8.4 Cowings, Toscano, DeRoshia, and Tauson, 1999.

The command and control (C2) vehicle (C2V) is required to support mobile operations and C2 within the confines of the vehicle. During early testing, it was discovered that human operators experienced motion sickness during moving

operations. As a result, the U.S. Army Research Laboratory's Human Research and Engineering Directorate and the National Aeronautics and Space Administration's Life Sciences Division performed a study to quantify the incidence and severity of motion sickness and any related performance decrement. The motion effects of the C2V parked, moving, and shortly halted were reported.

The main objectives were to (a) determine whether a significant difference existed among three internal configurations of the C2V or between seats within these vehicles; (b) determine whether a significant difference existed among the park, move, or short halt conditions; and (c) validate a method of converging indicators to assess the environmental impact of long space flights on crew members when a large sample of participants was used during ground-based operational conditions.

Twenty-four soldiers participated and were exposed to each of 12 seats (four seats in three configurations) for a 4-hour "cell". Three vehicle configurations were examined: (a) oblique, whereby the seat closest to the front faced forward and the other three seats were at 20-degree angle from the direction of travel; (b) perpendicular, whereby the front seat faced forward and the other three seats were at a 90-degree angle; (c) 4-forward, whereby all seats faced forward. Participants completed a motion sickness and mood scale and the delta cognitive battery for each cell. Half of the participants were instrumented to record physiological data. Each cell consisted of a parked administration of the test batteries, followed by two test batteries during motion and three test batteries during short halts.

Fifty-five percent of the participants reported moderate to severe motion sickness symptoms. The most frequently reported symptom was drowsiness (60% to 70% of participants), followed by headache (40% to 56%), sensations of increased warmth unrelated to ambient air temperature (40% to 45%), nausea (35% to 42%), and uncomfortable stomach sensations approaching nausea (20%). Short halts did not lessen symptoms. Performance was significantly degraded during moving operations versus the parked condition, with only a partial recovery during short halts. Performance degradation was comparable to blood alcohol levels at or above 0.08% (the legal limit of alcohol consumption in most states) in 35% of the soldiers during moving operations and 22% during short halts. No significant difference was reported between seat or vehicle in any of the measurements.

In summary, (a) there was no significant difference between vehicle configurations; (b) there was a negative impact on crew performance and health when subjects attended to visual computer screens while the vehicle was moving; (c) short halts did not substantially reduce symptom severity or

performance degradation; and (d) performance and mood were impaired in the vehicle, relative to pre- and post-tests conducted in a classroom facility.

It was suggested that the methodology used in this research project may be useful in the examination of the impact on soldiers in other land, sea, and air vehicles for which C2 functions similar to those of the C2V are planned. The examination of soldiers' physiological responses, performance, and mood states in these environments offers a more comprehensive assessment of the effectiveness of countermeasures for improving crew health and operational efficiency.

When asked about adaptation effects, Mr. Tauson responded via e-mail that the adaptation data were not included in the original report. As a result of some later questions, he reviewed the symptom data over time. The results are presented in two charts (see Figures 1 and 2). Basically, as would be expected, there was brief adaptation followed by an equalization in the first two-thirds of the chart. The increase in the last third is a little puzzling. Mr. Tauson believed that this was attributable to the introduction of a slightly different configuration or to the subjects' reaching some sort of endurance limit. It is possible that the subjects were reaching the point where their adaptive strategies were being overtaken by simple conditioning. In other words, the subjects' bodies knew what was going to happen.

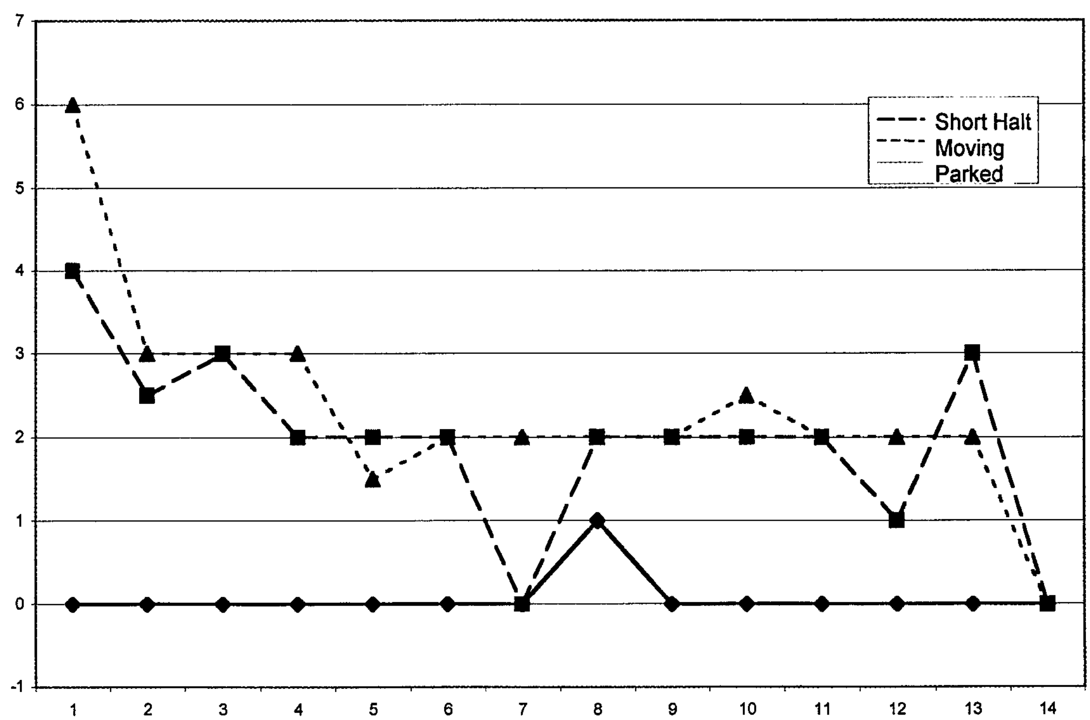


Figure 1. Median Symptoms Over Time.

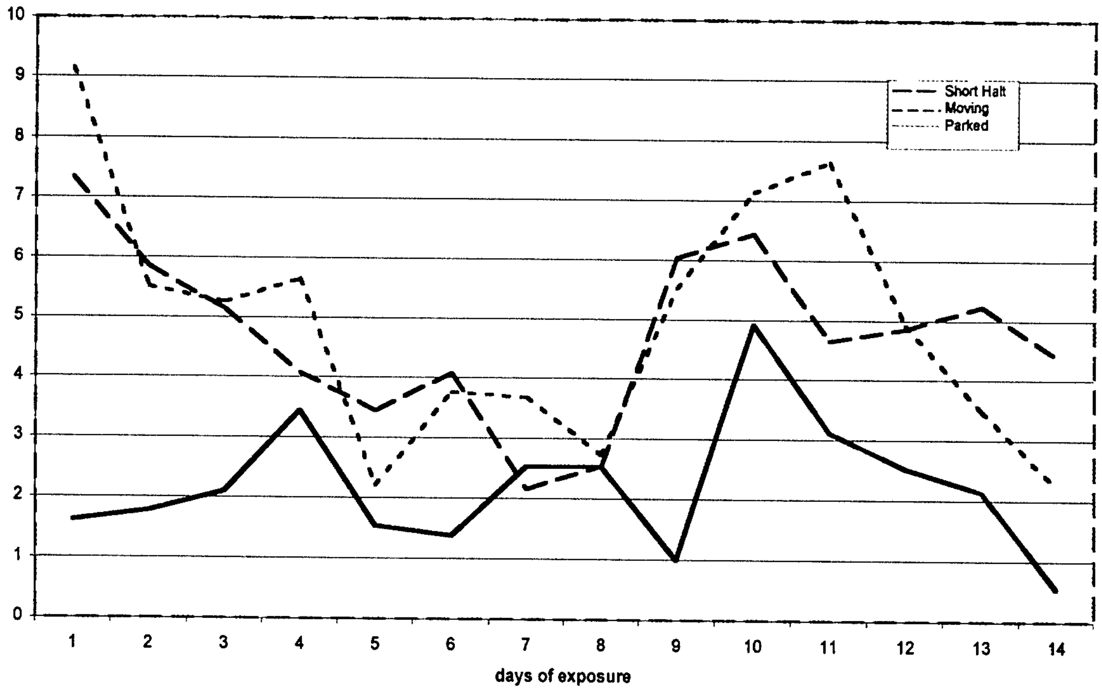


Figure 2. Mean Symptoms Over Time.

2.9 Air Sickness

2.9.1 Kennedy, 1975

Kennedy's objective was to show that training success can be predicted from motion sickness-related measures. The use of a motion sickness questionnaire to predict susceptibility to motion sickness or flight training success, depending on how the items are scored, was discussed. The motion sickness questionnaire (MSQ) was empirically validated against an experimental procedure for producing motion sickness symptomatology scores on the questionnaire, which were statistically related to the likelihood of successful aviation training. The MSQ inquired into each subject's exposure to motion, preferences for, and symptoms experienced in the devices. The subjects were then exposed to the Dial test, a standard and scorable procedure for producing motion sickness symptoms that is correlated with other motion sickness forms. A high score indicates resistance to MS since the score is the number of dial sequences attempted before emesis or requested nonparticipation. The group embedded figures test, another paper and pencil test, measured the field independence trait. The theory that motion sickness results from conflict of perceptual input is also discussed. High neuroticism scores were predictive for lack of success. Field independent persons seem less likely to attend to inappropriate fields. Field independence relates to an ability to separate figure from ground and to alternate between figure and ground. Also, the correlation between intellectual abilities scores (numerical and verbal ability, and mechanical aptitude) and field independence showed that common factors relating to flight training exist.

2.9.2 Jones, Levy, Gardner, Marsh, and Patterson, 1985

It was demonstrated that well-motivated fliers (military student pilots) with chronic, severe airsickness who were unresponsive to other treatment methods could return to unrestricted flying by using biofeedback-mediated self-regulation to enhance relaxation and lower autonomic arousal once nausea occurred. Elements of biofeedback training, autogenic training, mental imagery, deep muscle relaxation, systematic desensitization, diaphragmatic breathing, and occasional brief psychotherapeutic interventions were included in the application of the technique. Programs were tailored to each flier's particular personality style and autonomic response pattern. There was only a 15% failure rate of the biofeedback technique, attesting to this approach's effectiveness.

2.9.3 Johnson and Mayne, 1953

Earlier research showed that individual differences in susceptibility to motion sickness depend to a large extent on concurrent head movement in response to the movements imposed on the body as a whole. Statistics gathered from World War II show that airborne infantry are particularly susceptible to air sickness. As a result, it was decided that trials would be conducted with Army personnel in the process of training as paratroopers. In approximately 700 tests with more than 500 subjects (Canadian paratroop trainees), results showed that headrests have a consistent effect in preventing air motion sickness during air transportation in all turbulence conditions. It was possible to predict that in 95 of every 100 flights, between 60% to 83% of the susceptible Canadian paratroop trainees could avoid airsickness with the use of a headrest device during "normal turbulence." There is some indication that the incidence of air motion sickness in soldiers decreases as the time since the last meal increases; no general conclusions can be made with confidence.

3. Discussion

The literature revealed a myriad of possible causal factors and types and suggested remedies to reduce or potentially eliminate motion sickness symptoms and related performance decrements. Demographic factors that may influence motion sickness susceptibility are gender, exposure history, receptivity, adaptability, and personality characteristics. Unfamiliar and unexpected optical information may also provoke motion sickness. The primary theory of motion sickness is that of sensory conflict whereby signals from the visual, vestibular, and non-vestibular systems conflict with one another or with previous experience.

Some motion sickness symptoms in immersive virtual reality may be the result of resolution, field of view, and system lag. It is unlikely that sensory conflict is the

single causal factor in immersive reality. The impact of resolution and FOV on motion sickness is unclear. Woodman and Griffin (1977) reported that direction of head movement during Coriolis stimulation has a large effect on nausea. Rotating the head downward (pitched forward) rather than upward increases motion sickness symptoms. Vertical motion rather than horizontal has been found to be more provocative. Golding et al. (1995) revealed that upright versus supine body position and stimulation through the X-axis versus the Z-axis both enhance nauseogenicity of low frequency linear oscillation and these effects are additive. Active control, such as a driver or pilot compared to passengers, was found to play a role in motion sickness susceptibility and well-being. Active versus passive showed less decrement in well-being and reduced symptoms. Rolnick and Lubow (1991) showed that subjects who had control over their motion environment reported significantly fewer motion sickness symptoms and less of a decrement in well-being. Vogel et al. (1982) published that horizontal linear acceleration in a car when the stop-and-go technique was used is effective in provoking motion sickness. More than 43% became motion sick in less than 10 minutes. Finally, Cowings et al. (1999) reported a negative impact on crew performance and health when subjects attended to computer screens while the vehicle was moving.

Three primary classes of motion sickness symptoms were identified in the literature. The first class involves the vestibular system whereby there is a disruption of perceptual and sensorimotor activities, such as disorientation, dis-equilibrium, and inappropriate vestibulo-ocular or vestibulo-spinal reflexes. The second class has a perceptual origin and consists of many autonomic symptoms such as pallor, drowsiness, salivation, sweating, nausea, and vomiting. The third class includes symptoms such as mood changes, lethargy, and sleep and is referred to as the "sopite syndrome". This syndrome is a more recently discussed symptom class. None of the journal articles reviewed in this search specifically address the sopite syndrome. The causes of each symptom class vary over a wide range of mechanisms, including an individual's previous experience with motion and subsequent expectations.

The average exposure time in these research efforts was 30 minutes. In a combat environment, soldiers have to endure long miles in confined vehicles for several hours. Golding and Kerguelen were the only researchers who actually discussed recovery times. They reported that the slowest recovery time from low-frequency linear oscillation was 7 minutes. They warned that the subjective recovery time may be an underestimate of residual after-effects. Consequently, we do not know how soon a soldier could return to a full performance level after experiencing motion sickness.

Training techniques were discussed in 4 of the 21 journal articles reviewed. Toscano and Cowings (1982) revealed that subjects who were taught to control autonomic responses could withstand Coriolis acceleration stress as much as

three times longer after training. Dobie et al. (1989) showed that a combination of desensitization and cognitive therapy was most effective at increasing resistance to visually induced disorientation. Jones et al. (1985) reported a failure rate of only 15% for biofeedback-mediated self-regulation for enhancement of relaxation and lowering of autonomic arousal once nausea had occurred. Of 53 fliers grounded for chronic, severe motion sickness, 79% returned to and maintained satisfactory operational flying status, while 6% were partially successful following treatment. Dobie and May (1990) showed that tolerance in using one device can transfer to another motion experience. It appears that the best way to produce generalized motion adaptation is to subject the individual to a very provocative, perhaps vestibular, mode of stimulation.

Some other measures that may reduce motion sickness include seating configuration, vehicle design, positive head restraint, adequate external visual reference or artificial horizon, biofeedback, autogenic feedback training (individual taught to control autonomic responses), mental imagery, diaphragmatic breathing, and psychotherapeutic interventions.

Researchers have "standardized" several cognitive and physical performance measures to assess motion sickness severity, but few have addressed militarily relevant measures. Rolnick used the memory comparison task (MCT) and a dual task to assess performance. MCT is a computerized reaction time task. DT consisted of a tracking task and a continuous memory task. These would be applicable to drivers, commanders, command and control personnel, or infantry for example.

In a protocol to validate a motion sickness history questionnaire, ARL used a rail walk test (Heath, 1943) to measure locomotor coordination, a multi-task monitoring environment called SYNWORK (Elsmore, 1994; Lieberman, Mays, Shukitt-Hale, Chinn & Tharion, 1996) to measure cognitive performance, and an aiming performance test using the Noptel ST-2000 system. The rail-walking test consisted of three wooden rails 9 feet by 4 inches, 9 feet by 2 inches, and 6 feet by 1 inch. The height of each rail is sufficient to avoid contact of the participant's foot with the floor. Each rail was divided into units of feet. Each participant was asked to train on each rail by walking heel to toe. Scores were recorded before and after the study trial. The raw score was the total number of feet walked without the participant stepping off. SYNWORK consisted of a synthetic multi-task monitoring work environment for a personal computer. This test required continuous monitoring of four tasks: Sternberg memory; 3-column addition; visual tracking; and signal detection. The stimulation incorporated workload, resource sharing, and contingency factors. Scores were recorded before and after the trial. Aiming performance with the Noptel ST-2000 consisted of an optical unit attached to an air gun (no projectile used), a reflector attached to the target, and an interface box of electronics that connects the optical unit to a personal computer for data display, analysis, and storage.

Motion sickness severity was often defined through ratings such as those from a study performed by Golding et al. (1995): ratings 1 (no symptoms), 2 (mild symptoms, no nausea), 3 (mild nausea and any additional symptoms), and 4 (moderate nausea and any additional symptoms). These ratings varied from study to study.

4. Recommendations and Conclusions

The literature search revealed several potential motion sickness prevention methods. It is recommended that these prevention methods be researched to determine whether a benefit exists for indirect vision driving. The operator's seat should be designed to offer head restraint to limit independent head movement. This has been known to be highly effective in reducing motion sickness incidence. There is also considerable evidence that adopting the supine position reduces motion sickness symptoms.

During design, consideration should also be given to wave frequency in vertical periodic motion. It was determined that sickness incidence diminishes with increasing frequency and is nearly nonexistent above 0.6 Hz. Therefore, caution has been given against "smoothing" ride characteristics by reducing high frequency motion at the risk of increasing low frequency bands, thereby increasing the risk of motion sickness.

Another potential area of consideration is perceptual adaptation through prior exposure or training session. Unfamiliar and unexpected optical movement information can lead to motion sickness. In a moving combat vehicle, there will likely be many instances of unexpected optical information because of the jolts of riding and lack of situational understanding, for example. Little information was found about the effects of motion on perceptual and cognitive performance. Given that Future Combat Systems are emphasizing cognitive performance while the vehicle is moving, this is a major void in the research literature. Further research is needed in this area to identify the impacts on the various types of roles performed (e.g., command and control, infantry, medical, or vehicle operator). Emphasis should be placed on the organized development of measures sensitive to these roles and their relationship to vehicle characteristics.

Another possible method is to bring visual and vestibular cues into alignment through display resolution, FOV, and system lag. The impact that improved resolution or wide versus narrow FOV has on motion sickness is unclear. However, it is suggested that motion sickness symptoms increase with system lag. Further evidence suggests that sickness is caused by lag variation, not lag by itself. Display update lags may induce a conflict when time between head

movement and visual scene become discernible, for example. This issue weighs heavily with Future Combat Systems' use of numerous displays while moving.

Many researchers used motion sickness history questionnaires (MSHQ) as a means to predict susceptibility. MSHQs were designed to identify an individual's pre-exposure background or life's experiences to motion such as simulation, aviation, shipboard, and virtual environment (Kennedy, 1975; Miller & Graybiel, 1971). This questionnaire type varied since it is adapted to the specific research at hand. Dobie uses two rating checklists; one is an activity (individual experience) checklist and the other is a motion sickness (response to activities experienced) checklist. Dobie adds activities such as carnival rides, swings, elevators, and bicycles to his checklists. Another questionnaire type often used in conjunction with the MSHQ was a symptomatology questionnaire (Kennedy, 1975) that was used to rate the type and degree of motion sickness experienced during a specific exposure.

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References

Benson, A.J., and Reason, J.T. (1965). *The effects of hyoscine upon the perception of motion after-effects*. Unpublished report.

Brand, J.T., & Reason, J.J. (1975). *Motion sickness*. London: Academic Press.

Cowings, P.S., & Toscano, W.B. (1982). The relationship of motion sickness susceptibility to learned autonomic control of symptom suppression. *Aviation, Space, and Environmental Medicine, 53(6)*, 570-575.

Cowings, P.S., Toscano, W.B., DeRoshia, C., & Tauson, R.A. (1999). *The effects of the command and control vehicle (C2V) operational environment on soldier health and performance* (ARL-MR-468). Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Dobie, T.G., & May, J.G. (1990). Generalization of tolerance to motion environments. *Aviation, Space, and Environmental Medicine, 61*, 707-711.

Dobie, T.G., May, J.G., Fisher, W.D., & Bologna, N.B. (1989). An evaluation of cognitive-behavioral therapy for training resistance to visually induced motion sickness. *Aviation, Space, and Environmental Medicine, 60*, 307-314.

Elsmore, T.F. (1994). SYNWORK1: PC-based tool for assessment of performanc e in a simulated work environment. *Behavior Research Methods, Instruments, & Computers, 26*, 421-426.

Elsmore, T.F., Naitoh, P., & Linnville, S. (1992). *Performance assessment in a sustained operations using a computer-based synthetic work task* (NHRC Technical Report No. 92-30). San Diego, CA: Naval Health Research Center.

Dolezal, H., Connon, T., & O'Neal, M. (December 1985). *Optical disorientation on task performance and motion sickness* (AA MRL-TR-85-079). Wright-Patterson AFB, OH: Harry G. Armstrong Aerospace Medical Research Lab.

Golding, J.F., & Kerguelen, M. (1992). A comparison of the nauseogenic potential of low-frequency vertical versus horizontal linear oscillation. *Aviation, Space, and Environmental Medicine, 63*, 491-7.

Golding, J.F., Phil, D., Markey, H.M., & Stott, J.R.R. (1995). The effects of motion direction, body axis, and posture on motion sickness induced by low

frequency linear oscillation. *Aviation, Space, and Environmental Medicine, 66,* 1046-51.

Graybiel (1965). Functional disturbances of vestibular origin of significance in space flight, *Second International Symposium on Basic Environmental Problems in Space.* Paris, France.

Heath, S.R. Jr. (1943). The military use of the rail-walking test as an index of locomotor coordination. *Psychological Bulletin, 40,* 282-284.

Irwin (1881). The pathology of seasickness. *Lancet, ii,* 907-909.

Johnson, W.H., & Mayne, J.W. (October 1953). Stimulus required to produce motion sickness. Restriction of head movement as a preventive airsickness--field studies on airborne troops. *Aviation Medicine, 1/2,* 400-411.

Jones, D., Levy, R., Gardner, L., Marsh, R., & Patterson, J. (December 1985). Self-control of psychophysiologic response to motion stress: Using biofeedback to treat airsickness. *Aviation, Space and Environmental Medicine, 56,* 1152-1170.

Kennedy, R.S. (November 1975). Motion sickness questionnaire and field independence scores as predictors of success in Naval aviation training. *Aviation, Space, and Environmental Medicine, 46(11),* 1349-1352.

Kennedy, R.S., Fowlkes, J.E., Berbaum, K.S., & Lilienthal, M.G. (July 1992). Use of a motion sickness history questionnaire for prediction of simulator sickness. *Aviation, Space, and Environmental Medicine, 63,* 588-93.

Kennedy, R.S., & Graybiel, A. (1965). *The dial test: A standardized procedure for the experimental production of canal sickness symptomology in a rotating environment* (NSAM-930). Pensacola, FL: U.S. Naval School of Aviation Medicine.

Lawson, B.D., & Mead, A.M. (1998). The sopite syndrome revisited: Drowsiness and mood changes during real or apparent motion. *Acta Astronautica, 43(3-6),* 181-192.

Lawther, A., & Griffin, M.J. (1986). The motion of a ship at sea and the consequent motion sickness amongst passengers. *Ergonomics, 29,* 535-552.

Lieberman, H.R., Mays, M.Z., Shukitt-Hale, B., Chinn, K.S.K., & Tharion, W.J. (1996). Effects of sleeping in a chemical protective mask on sleep quality and cognitive performance. *Aviation, Space, and Environmental Medicine, 67,* 841-8.

Manning, G.W. (1943). *Acclimation to swing sickness.* Report to Assoc. Comm. on Aviation Medicine Research. Canada: NRC.

Manning, G.W., & Stewart (1949). Effect of body position on incidence of motion sickness. *Journal of Applied Physiology, 1,* 619-628.

Miller, E.F., & Graybiel, A. (1970). A provocative test for grading susceptibility to motion sickness yielding a single numerical score. *Acta Oto-laryngologica, Supplement 274.*

Morton, G., Cipriani, A., & McEachern, D. (1947). Mechanism of motion sickness. *Archives of Neurology and Psychiatry, 57,* 58-70.

Reason, J. (1978). Motion Sickness: Some theoretical and practical considerations. *Applied Ergonomics, 9.3,* 163-167.

Regan, E.C. (1995). NATO research study group 16 workshop presentation--Some effects of using virtual reality technology: Data and suggestions.

Rolnick, A., & Bles, W. (August 1989). Performance and well-being under tilting conditions: The effects of visual reference and artificial horizon. *Aviation, Space, and Environmental Medicine, 60,* 779-785.

Rolnick, A., & Lubow, R.E. (1991). Why is the driver rarely sick? The role of controllability in motion sickness. *Ergonomics, 34(7),* 867-879.

Sharkey, T., McCauley, M., Schwirzke, M., Casper, P., & Hennessy, R. (February 1995). *The effects of whole body motion, head-mounted display, and hand control device on tracking performance.* Warren, MI: U.S. Army Tank-Automotive Command, TARDEC.

Tauson, R.A. (February 25, 2002). E-mail message, Subject: Motion sickness and C2V experiments. Aberdeen Proving Ground, MD: U.S. Army Research Laboratory.

Tiande, Y., & Jingshen, P. (1991). Motion sickness severity under interaction of vection and head movements. *Aviation, Space, and Environmental Medicine, 62,* 141-4.

Toscano, W.B., & Cowings, P.S. (1982). Reducing motion sickness: A comparison of autogenic feedback training and an alternative cognitive task. *Aviation, Space, and Environmental Medicine, 53(5),* 449-53.

Turner, M., & Griffin, M. (1999). Motion sickness in public road transport: Passenger behavior and susceptibility. *Ergonomics, 42(3)*, 444-461.

Vogel, H., Kohlhaas, R., & von Baumgarten, R.J. (1982). Dependence of motion sickness in automobiles on the direction of linear acceleration. *European Journal of Applied Physiology, 48*, 399-405..

Wendt, G.R. (1968). Experiences with research on motion sickness. *Fourth Symposium on the Role of Vestibular Organs in Space Exploration*, NASA SP-187, Pensacola, Florida.

Wiker, S.F., Kennedy, R.S., McCauley, M.E., & Pepper, R.L. (1979). Susceptibility to seasickness: Influence of hull design and steaming direction. *Aviation, Space, and Environmental Medicine, 50(10)*, 1046-1051.

Woodman, P.D., & Griffin, M.J. (1997). Effect of direction of head movement on motion sickness caused by Coriolis stimulation. *Aviation, Space, and Environmental Medicine, 68*, 93-8.

Yardley, L. (1992). Motion Sickness and Perception: A reappraisal of sensory conflict approach. *British Journal of Psychology, 83*, 449-471.

APPENDIX A

SUMMARY CHART

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Author(s)	Publication Date	Type of motion sickness	Sample Size	Performance measure	Method and Performance Degradation	Conclusions
Reason	1978	General; review of theoretical and practical considerations	N/A	N/A	Discussion of sensory rearrangement theory that considers a mismatch in spatial senses (principally the eyes, the vestibular system, and the proprioceptive receptors in the joints, tendons, and muscles). Quantitative studies of vertical periodic motion are also discussed. It is noted that sickness incidence diminishes with increasing frequencies and is generally non-existent above 0.6 Hz. Individual characteristics (sex, age, exposure history, receptivity, adaptability, and personality characteristics) known to be associated with susceptibility, and anti-motion sickness drugs are briefly summarized.	Motion sickness (MS) appears to be triggered by a mismatch between current input from position and motion senses and stored patterns derived from recent transactions with the spatial environment. Recommendations for effective MS prevention include a combination of good vehicle and seating design, adequate passenger information concerning behavioral control measures, and appropriate drug administration.
Dolezal, Connon, O'Neal	1985	Manipulated visual environment, space motion sickness (SMS), a prism is worn that optically reverses the field of view (FOV).	15	Six visually guided fine motor coordination tasks, MS ratings	1. Significant covariations for 13 of 15 subjects for symptom ratings and physiological responses 2. Modest but significant covariations for 15 subjects as a group for MS symptom ratings and magnitude of physiological responses 3. Measurable changes from baseline levels as a group for physiological responses 4. Significant individual differences exist among subjects for all physiological motion sickness rating scale (MSRS) parameters. 5. As a group, subjects (Ss) perceptions of bodily discomfort differed substantially from baseline levels as reflected in MSRS ratings. 6. Ss displayed significant loss of control in visually directed body balance in the reversing prism condition as reflected first, in the One Leg Balance Test where Ss were able to stand, on average, only 1/10th as long as in the Baseline (no prism) condition and, second, Ss made an average of 4 times as many false starts awhile trying to stand on	Unfamiliar and unexpected optical movement played a prominent role in MS.

Author(s)	Publication Date	Type of motion sickness	Sample Size	Performance measure	Method and Performance Degradation	Conclusions
					one leg in the Experimental condition. 7. Three to 16 times as long to perform six eye-hand coordination tasks in the experimental (reversing prism) versus baseline (no prism). 8. Rapid adaptation in fine motor coordination--Ss completed eye-hand coordination tasks on a second attempt in the Experimental (reversing prism) condition in as much as one-fourth of the time.	
Dobie, May, Fisher, and Bologna	1989	Visually induced	32	MS history questionnaire, symptom checklist, tolerance scores, magnitude estimation scores	Ss were assigned to one of four groups, based on their ability to tolerate visually induced apparent motion (VM) as defined by responses to a MS history questionnaire. Group I received cognitive therapy only. This group received 10 sessions. Session 1 lasted 1 to 1.5 hours; Sessions 2 through 9 lasted 20 min, and the last session lasted 10 min. Group II received desensitization training only. This group received 10 sessions. Session 1 represented 75% of their initial pretest run duration. In Sessions 2 and 3, the duration was increased by increments of 5%, and in the remaining sessions by increments of 15%. Group III received a combination of desensitization and cognitive therapies (cognitive-behavioral therapy). This group received confidence-building counseling and repeated exposure to visual stimulus. Session 1 was the same as the Cognitive-only group, but Sessions 2 through 10 were 20 min. long. Exposure duration for desensitization was determined by the experimenter as in the desensitization only group. Group IV received no treatment. Mean post-test tolerance scores (computed as latency to trial termination as determined by the S to be the detection of MS symptom onset) revealed that only the cognitive-behavioral and cognitive-only group increased their	The major finding supports the belief that cognitive-behavioral treatment provides significant therapeutic support for those who are highly susceptible to visually induced MS. The results suggest that the combination of the cognitive therapy and desensitization is the most effective at increasing resistance to visually induced disorientation. Only desensitization does not hold promise as a treatment technique since results did not differ from those of the control group.

Author(s)	Publication Date	Type of motion sickness	Sample Size	Performance measure	Method and Performance Degradation	Conclusions
					tolerance to VM stimulation. An ANOVA showed a significant main effect for cognitive treatment ($F = 15.52$; df 1, 28; $p < 0.0005$), a significant main effect for tests ($F = 74.68$; df 2, 56; $p < 0.00001$), a significant Cognitive x Tests interaction ($F = 53.83$, df 2,56; $p < 0.00001$), a significant Desensitization x Tests interaction ($F = 5.46$; df 2, 56; $p < 0.0068$) and a significant Cognitive x Desensitization x Tests interaction ($F = 5.01$; df 2, 56; $p < 0.01$). Newman-Keuls' tests showed that only the post-test means for the groups receiving the cognitive component were significantly different ($p < 0.00001$) from the other means and that the mean for the combined group was significantly greater than that for the cognitive-only group. Of 21 items on the symptom checklist, only two (general discomfort and stomach awareness) yielded unambiguous and significant pre-post counseling interaction (general discomfort $F = 5.54$; df 1,28; $p < 0.03$); (stomach awareness $F = 7.30$; df = 1, 28; $p < 0.01$). Newman-Keuls' tests for both symptoms indicated that the mean for those who received counseling was significantly reduced after treatment ($p < 0.006$, and $p < 0.01$, respectively). This indicated that only two items on the checklist were used consistently by the Ss. Three magnitude estimates were made following the second pretest and post test: self-vection, drum movement, and motion sickness. An ANOVA revealed only significant effects for MS. The most marked decrease occurred in the group that received both cognitive counseling and desensitization. The main effect of tests was marginally significant ($F = 4.13$; df = 1, 28; $p < 0.0517$); the interactions for tests by cognitive counseling ($F = 7.68$; df 1, 28; $p < 0.0098$); and tests by cognitive counseling by desensitization	

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					(F = 5.77; df 1, 28; $p < 0.0232$) were both significant. Newman-Keuls' tests revealed three significant differences between post-test means. The combined group mean differed significantly from the means of the desensitization group ($p < 0.0040$), the cognitive counseling group ($p < 0.0266$), and the control group ($p < 0.0296$).	
Dobie and May	1990	Visually induced; a circular drum, a rotating chair, and a standard video monitor	20	external-internal locus of control scales, general trait anxiety scale, symptom checklist, and magnitude estimates to indicate the degree of self-motion, drum rotation and MS upon cessation of stimulation	Ss were assigned to one of four groups by matching their mean tolerance to visually induced motion after being pre-tested in a Dichgans and Brandt drum with a visual display terminal of an expanding surface (displayed a white square that expanded in size from 1 to 9 deg of visual angle over repeated periods), and on a revolving and tilting chair. The first group was the control group and received only cognitive counseling. Ss in the other groups received the same cognitive counseling in addition to incremental exposures to the drum, chair, and video monitor, respectively. The mean pre-test scores were higher and more variable for the video monitor as compared to the drum and chair. The mean post-test scores for all except the drum group increased on all devices. An ANOVA revealed significant main effects for mode of stimulation (F = 60.70; df = 2, 32; $p < 0.0001$) and pre and post testing (F = 50.04; df 1, 16; $p < 0.0001$). A three-way interaction (Mode of Stimulation x Groups x Pre and Post) was significant (F = 2.64, df 6, 32; $p < 0.0341$). Newman-Keuls' tests revealed that mean tolerance scores differed significantly from pre and post testing for the drum and chair groups when the drum was used ($p < 0.002$ and 0.02, respectively) and for the chair group when the chair was used ($p < 0.004$).The greatest declines in symptomatology	Results showed that treatments involving the chair and the drum provided a generalized tolerance to visually induced motion. The results support the idea that there are both specific and general components in learning to tolerate motion environments. The major finding was support for the belief that tolerance acquired with one device can transfer to another motion experience. This seems to depend on the severity of the motion stimulus used during treatment. It appears that the most efficacious way to produce generalized adaptation to motion environments is to employ a very provocative, perhaps vestibular, mode of stimulation.

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					occurred with the video and chair. An ANOVA revealed significant main effects for mode of stimulus (F = 6.44; df 2, 32 $p < 0.0045$)and pre and post testing (F = 14.98; df 1, 16; $p < 0.0014$). Newman-Keuls' tests indicated that significant pre-post differences occurred for the chair ($p < 0.0183$) and video ($p < 0.0072$) but not for the drum. Magnitude of estimation scores declined for all groups on each device. An ANOVA indicated significant main effects for mode of stimulus (F = 52.57; df 2,32; $p < 0.0001$) and pre and post testing (F = 27.50; df 1, 16; p<0.0001), a significant two-way interaction between these two factors (F = 6.00;df 2,32; $p < 0.0061$), and a significant three-way interaction (F = 3.11; df 6, 32; $p < 0.0163$). Newman-Keuls' tests revealed significant pre and post differences for the magnitude estimates when testing in the chair, for the control ($p < 0.0001$), and chair ($p < 0.0044$) groups; and for the drum in the control ($p < 0.0200$) and drum ($p < 0.0003$) groups. There were no main effects for the personality scales pre and post ANOVAs.	
Tiande and Jingshen	Feb 1991	rotating sphere	26	MS symptom form, illusory self-motion sensations form	The S sat on a chair in a vertical posture with the head centered in the rotating sphere. Three types of circular vection included yaw vection from the sphere rotating clockwise about the vertical spinal axis (Z-axis); pitch vection resulting from the upward rotation of the sphere about the horizontal coronal axis (Y-axis); and roll vection resulting from the sphere rotating clockwise about the horizontal visual axis (X-axis). For each condition of circular vection, there were four different head conditions: the head-still condition where the S kept his body and head stationary; the pitch head-movement condition where the S bowed the head forward and	Yaw vection combined with pitch or roll head movements significantly increased MS. Pitch vection with any type of head movement or head or scene rotation about the same axis significantly reduced MS. When the head was stationary, MS was highest in pitch vection, lowest in yaw vection, and moderate in roll vection. Tables containing average scores and incidence of MS symptoms as related to head

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					backward about the Y-axis; the roll head-movement condition where the S tilted the head from shoulder to shoulder about the X-axis; the yaw head-movement condition where the S swiveled the head side to side about the Z-axis. Under yaw vection, pitch and roll of head movements significantly increased the scores of MS symptoms ($p < 0.05$) as compared to the head-still conditions. Under pitch vection, pitch, roll, or yaw head movements significantly reduced the scores of MS symptoms ($p < 0.05$). When head movements were confined to the same axis as circular vection, the MS symptoms were suppressed as compared to pure vection stimulation without head movement. Combinations of pitch vection and pitch head movement, or roll vection and roll head movement significantly reduced the scores of MS symptoms ($p < 0.05$). The MS symptom score of yaw head movement combined with yaw vection was less than in pitch ($p < 0.05$) or roll head movement with yaw vection.	conditions are provided in this article.
Woodman and Griffin	Feb 1997	Coriolis stimulation	24	subjective illness ratings	Ss were blindfolded and trained to make 30° pitch motions of the head every 30 seconds while rotating about a vertical axis at 10 rpm on a turntable at two separate locations: a) at the center of rotation; b) 0.75 m from the center of rotation. Following each head movement, the Ss rated their MS. The reported symptoms varied between Ss from simply becoming tired to slight dizziness to very nauseous.	Precise location of the body at the center of rotation is not critical during Coriolis stimulation, but the direction of head movement has a large effect on nausea. Ss responded that rotating their heads downward (i.e., pitch forward) gave rise to increased MS symptoms than did rotating their heads upward. There were no significant differences between the ratings given by men and women either at the center of rotation or the radius of rotation.

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Cowings and Toscano	1982	Coriolis-induced MS	24 men randomly assigned to four equal groups matched in terms of Coriolis sickness susceptibility index (CSSI). Two groups were highly susceptible and two were moderately susceptible.	Six Coriolis Sickness Susceptibility Index (CSSI) tests. See Method and Performance Degradation section in this chart for further explanation.	The CSSI tests consisted of initiating rotation of 6 rpm (0.628 rad/s) and incrementing by 2 rpm (0.209 rad/s) every 5 min. The rotational velocity was held constant during each 5-minute interval. The maximum velocity was 30 rpm (3.142 rad/s). Ss executed 150 head movements at 45-deg angles during each 5-min period. Instructions for making head movements were provided via tape-recorded voice. Head movement direction was randomized. Padded headrests mounted 45 deg from the vertical on the left, right, front, and back of the chair enabled the blindfolded Ss to execute randomized head movements in these directions. There was a 30-s pause (no head movements but rotation continued) between each 5-min step to administer the diagnostic scale. CSSI tests were terminated at 30 rpm or at a malaise level of 111. Autogenic feedback training (AFT), where Ss are taught to control their autonomic responses, was provided to the treatment groups.	Both treatment groups significantly improved performance on CSSI tests after training; neither of the control groups changed significantly. Highly and moderately susceptible Ss in the two treatment groups improved at comparable rates. Highly susceptible control group Ss did not habituate across tests as the moderately susceptible controls.
Toscano and Cowings	1982	Coriolis-induced MS	18 men were randomly assigned to three groups matched in terms of CSSI.	6-Coriolis sickness susceptibility	Group I was taught to control their autonomic responses before the third, fourth, and fifth CSSI tests (6 hr total training). Group II was given "sham" training in an alternate cognitive task during conditions otherwise identical to those of Group I. Group III received no treatment. A significant difference in performance across tests, $F(5, 75) = 8.874$, $p < 0.001$, and between groups, $F(2, 75) = 4.193$, $p < 0.05$. Changes in performance across	Treatment group I Ss showed that they could withstand Coriolis acceleration stress significantly longer after 6 hours of training.

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					tests were significantly different among groups, F (10, 75) = 6.173, $p < 0.001$. On the fifth CSSI test, when training was completed (total 6 hr), the treatment group Ss performed significantly better than either control group: Group I and Group II, t (10) = 2.39, $p < 0.025$; Group I and Group III, t (10) = 2.29, $p < 0.025$.	
Miller and Graybiel	1970	Coriolis-induced; Stille Rotary chair	253	Motion Experience Questionnaire	Ss were required to move their heads 90 deg in the frontal and sagittal planes while seated in a chair that rotated. CSSI was determined for each subject by multiplying the average stress effect of each head movement by the revolutions per minute used, by the number of head movements required to provoke severe malaise (MIII). The procedure yielded high test-retest reliability in terms of CSSI scores and pattern of symptomatology. Malaise was rated as follows: MI = slight malaise; MII = moderate malaise; MIII = severe malaise.	The CSSI distribution values revealed that normal individuals are moderately to highly susceptible to Coriolis stress. Ss lacking normal vestibular function (as determined by specific medical tests including otolith and semi-circular canal function and oculogyral illusion threshold) remained symptomless when exposed to the severest Coriolis acceleration. However, three Ss with normal vestibular function were also resistant to the severest acceleration, demonstrating marked individual differences in susceptibility. The stability of the results renders this test useful in determining individual susceptibility and the influence of such factors as drugs and training.
Regan	1995	Immersive Virtual Reality (VR)	150	1-6 malaise scale, standard simulator sickness questionnaire	Ss were immersed in a VR system for 20 minutes. A Provision 200 VR system was used with a Virtual Research Flight Helmet and a Polhemus tracking system. Sixty-one percent of Ss experienced symptoms of illness at some point during the 20-minute immersion and 10-minute post immersion	Results show a high incidence of self-reported malaise resulting from the use of immersive VR system. Symptoms ranged from headaches and eye strain to severe nausea. The data suggested that

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				(Kennedy et al., 1993)	period. Five percent withdrew because of the severity of their symptoms. The main significant problems were nausea followed by disorientation and oculomotor problems.	adverse side effects produced by the immersive VR technology may be sufficiently common to threaten future successful research with the VR system and of applications of the technology in its present state of development.
Golding and Kerguelen	June 1992	Low frequency linear oscillation, comparison of sitting upright versus supine through the Z-axis	12	Reason and Brand MS suscepti-bility question-naire, Subjective MS self-rating, and visual search task	The visual search task required each subject to search for a number as defined by the intersection of a letter (column) and number (row) combination. Analysis of covariance for sickness rating as covariant of performance, removing any time, subject, and vertical or horizontal effects, revealed a small but significant relationship between deviation in performance ($r = -0.21$, df 120, 2-tailed $p < 0.05$). Subjects averaged 8.8 responses per minute (correct responses averaged 8.7 per minute). There was correspondence to a reduction in response rate by approximately two responses per minute across the extremes of sickness rating from "feeling OK" to "moderate nausea".	Results showed that vertical motion was clearly more provocative than horizontal. Performance of the search task was hampered by MS.
Golding, Markey, Stott	Nov 1995	Low frequency linear oscillation	Experiment 1: 28 Experiment 2: 12	Reason and Brand MS suscepti-bility question-naire, sickness ratings and symptom checklist, visual search matrix	A: seated upright, with horizontal motion, X-axis; B: seated upright, with vertical motion, X-axis; C: supine, with vertical motion, X-axis. (Note: X = horizontal head-body alignment; Z = vertical head-body alignment) Exp. 1: (exposed to condition A & B) The time to achieve sickness ratings 2 (mild symptoms, no nausea), 3 (mild nausea and any additional symptoms), 4 (moderate nausea and any additional symptoms) was significantly shorter for horizontal (A) than for vertical motion (B), as shown by significant ANOVA motion condition effects for rating 2 ($F = 24.7$ $df = 1, 26$ $p < 0.0001$), for rating	Results from this study and a previous study (Golding & Kerguelen, 1992) suggest that the upright and stimulation-through-the-X-axis conditions both enhance nauseogenicity of low frequency oscillation more than the supine position and the Z head-body axis. The effects are additive. A less important factor is motion direction with respect to the gravity vector (horizontal versus vertical).

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					3 (F = 31.6 df = 1, 26 $p < 0.0001$), and for rating 4 (F = 51.9 df = 1, 26 $p < 0.0001$). Total symptom scores at motion end point were significantly less for condition B than A. This was because of lower symptom scores in 10 of 28 Ss in the vertical condition who failed to achieve a sickness rating of 4 before the 30-min. time limit. Once these Ss were eliminated, there was no significant difference between conditions for total symptom scores (F = 0.09, df = 1, 16 p = ns). Exp. 2: (exposed to conditions A, B, and C) There was a significant effect of time to sickness rating 3 for motion condition for all Ss (F = 4.3 df = 2, 12 $p < 0.05$). Examination of means and specific comparisons, using all Ss or estimated values, showed that time to reach sickness stages 3 and 4 was significantly less for A than B ($p < 0.05$).	
Kennedy, Fowlkes, Berbaum, and Lilienthal	July 1992	simulator sickness	456	motion history questionnaire (MHQ), motion sickness questionnaire (MSQ)	Four MHQ scoring keys were compared: (1) Coriolis Stimulation (CS); (2) Very Low Frequency Stimulation - High Incidence (VLF-H); (3) Very Low Frequency - Low Incidence (VLF-L); (4) Simulator sickness (SS). Inter-correlation of dependent measures (pre-post difference scores and post scores) was very high (r = 0.86; $p < 0.01$). Correlations of the SS key with CS, VLF-H, and VLF-L imply 50% common variance. Comparing the four keys, higher overall correlations were found between SS ($p < 0.001$), CS ($p < 0.001$), and the criteria.	Although all scoring keys were predictive of reported MS symptoms, the highest correlations were those obtained with the SS key. Therefore, it is recommended that the SS key be used for the MHQ as a predictor of simulator sickness since it possesses a greater predictive validity. Pilots may be made aware of their risk for developing simulator sickness and may familiarize themselves with guidelines to reduce symptoms. This action, in turn, may reduce safety risk, optimize training, and avoid flight restrictions that would otherwise be imposed if symptoms were present.

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Rolnick and Bles	1989	Sea sickness	12	Memory Comparison Task (MCT) - a computerized reaction time task; Dual Task (DT) - consisted of a tracking task and a continuous memory task; a MS questionnaire and a verbal rating of well-being 100 (excellent) and 0 (very bad).	Ss were exposed to angular motion in a tilting room during three experimental conditions: a) Closed cabin (CC) - Windows covered, no visual reference from the outside world; b) Windows (W) uncovered, a partial view of the environment; c) Artificial Horizon (AH) - Windows covered, a horizon projected on the walls by a rotating laser beam. For MS, an ANOVA for repeated measures revealed a significant main effect for the conditions ($F = 4.06$, $p < 0.05$). *A posteriori* analysis showed a significant difference between CC and AH conditions ($t = 1.82$, $p < 0.05$) and a significant difference between W and CC conditions ($t = 2.94$, $p < 0.05$). For well-being, an ANOVA for repeated measures showed a significant effect for exposure duration ($F = 11.86$, $p < 0.05$) but only a marginal effect for conditions ($F = 2.74$, $p < 0.08$). For performance measures, an ANOVA for repeated measures showed a significant effect for conditions ($F = 3.19$, $p < 0.05$) and for time ($F = 12.18$, $p < 0.01$). *A posteriori* analysis indicated that condition CC was significantly different from no motion (NM) ($t = 2.35$, $p < 0.05$) and from W ($t = 2.05$, $p < 0.05$) but not from AH.	The main conclusion was that roll and pitch motion result in performance deterioration and a well-being decrement. These effects may be reduced by providing a visual reference frame, even a single projected artificial horizon.
Wiker, Kennedy, McCauley, and Pepper	May 1979	Sea MS	18	Subjective symptom questionnaire, objective evidence - reporting of vomiting episodes	Significant covariance between the magnitude of MS symptomatology and the encounter direction of the primary swell ($p < 0.01$). Significant correlations were found between sickness severity and subject concentration, fatigue, urine production, and urine specific gravity.	Sea state, vessel encounter direction to the primary swell and hull design characteristics play a major part in the provocation of MS aboard marine vehicles. The 89 Navy experimental vessel (semi-submersible platform or SSP), which represents a radical change from the traditional mono-hull ship design, produced only very minor levels of illness, which

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						were equivalent to those levels produced by the much larger and heavier Coast Guard White High Endurance Cutter
Rolnick and Lubow	1991	Automobile	44	5-point MS rating scale, 11-point well-being scale, motivation measure	Twenty-two pairs of yoked Ss were exposed to nauseogenic rotation. One S of each pair had control over the rotation and head movements. The other was passively exposed to the same motion stimulus. A t-test (one tail) of the MS symptoms as a function of control revealed a significant difference between the two groups ($t = 2.05$, $df = 42$, $p < 0.05$). Well-being decreased with time of rotation, with no-controllability group showing an increased rate of decline in well-being. Ss verbally reported a number (0 = I feel fine, 10 = I feel awful), reflecting their well-being before the experiment and at 3 minutes and 6 minutes into the rotation. These conclusions were supported by an ANOVA that revealed the main effects for groups ($F(1, 42) = 24.01$ $p < 0.001$) and for time ($F(2, 84) = 564.29$, $p < 0.001$), and a significant Time x Group interaction ($F(2, 84) = 22.2$, $p < 0.001$). There was no significant difference for the S's estimation of time to continue with the experiment.	Those Ss who had control reported significantly fewer MS symptoms and less of a decrement in their well-being.
Vogel, Kohlhaas, and von Baumgarten	1982	Automobile	38	special motion sickness scaling index	Ss were studied in an accelerating ambulance car in one of the following positions: (1) sitting upright facing forward in the car; (2) lying supine on a stretcher head forward; (3) supine position head backward. Consecutive short periods of negative horizontal acceleration were achieved by brisk braking followed by weak re-acceleration.	Results clearly show that horizontal linear acceleration in a car when the stop-and-go technique is used is effective in provoking MS. More than 43% of the Ss became motion sick in fewer than 10 minutes.
Turner and Griffin	1999	Bus (coach) MS	3256	14-item questionnaire. The	A significant positive correlation was found between symptom scores and passenger illness ratings ($r = 0.69$, $p < 0.001$). Illness ratings, symptom scores,	Overall, 28.4% of passengers reported feeling sick, 12.8% reported nausea, and 1.7%

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				validity of this scale has been examined in a previous MS survey (Lawther & Griffin, 1986).	and vomiting varied significantly as a function of travel activity. Activity consisted of four types: internal visual (reading, watching videos, playing computer or card games); external visual (looking out the window); active (talking); and passive (resting, sleeping, listening to music or doing nothing). Illness was greatest for passive activity and lowest for external visual activity. No significant differences were found in illness ratings, symptom scores, or vomiting occurrence as a function of quantity of food consumed. Passenger age was significantly correlated with illness ratings (r = -0.81, $p < 0.001$), symptom scores (r = -0.82, $p < 0.001$), and vomiting occurrence (r = -0.57. $p < 0.001$), suggesting that older passengers suffered less travel illness. Passengers with no forward view reported significantly greater illness ratings, symptom scores, and vomiting occurrence than those who had a view of the road. Illness ratings, symptom scores, and vomiting occurrence were significantly greater for passengers in aisle seats than for passengers in window seats. Susceptibility ratings were negatively correlated with passenger age (r = -0.20, $p < 0.001$) and positively correlated with passenger illness ratings (r = 0.40, $p < 0.001$) and symptom score (r = 0.40, $p < 0.001$). There were significant differences in illness ratings, symptoms scores, and vomiting as a function of travel regularity, with less frequent travelers experiencing greater sickness.	reported vomiting during coach travel. Travel sickness decreased with increasing age and greater travel experience. Females reported being very sick more often than men by a 4:3 ratio. Poor forward visibility increased illness. Illness was three times higher for passengers with no view of the road ahead (mean, 34.6%) as compared to those who could see very well (mean, 12.7%). No relationships were found between sickness and temperature and time of travel.
Cowings, Toscano, DeRoshia, Tauson	Nov 1999	Vehicle	24	MS and mood scale, Delta cognitive battery	Performance was significantly worse during moving operations than in parked condition with a partial recovery during short halts. Performance degradation was comparable to blood alcohol equivalencies at or above 0.08% (the legal limit of alcohol	1. A negative impact on crew performance and health when Ss attended to computer screens while the vehicle was moving. 2. Symptom severity and

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					consumption in most states) in 35% of the soldiers during movement and 22% during short halts.	performance degradation were not substantially reduced by intermittent short halts. 3. Performance and mood were impaired by 10% in the vehicle during park condition, relative to pre and post tests conducted in a classroom facility.
Kennedy	1975	air sickness	100	MS questionnaire (MSQ), Dial Test (Kennedy & Graybiel, 1965)	MS questionnaires were administered; then the Ss were exposed to the Dial test (a standardized, scorable procedure for producing MS symptoms, which is correlated with other forms of MS; a high score indicates resistance to MS since the score is the number of dial sequences attempted before emesis or requested nonparticipation) aboard the slow rotation room (SRR). A high correlation was found between the MSQ and Dial test scores (r = 0.46; N=100; $p < 0.01$). To make the scoring less subjective and repeatable, an item analysis of the MSQ questionnaire of the 27 highest and 27 lowest Dial test scorers (N = 52) was conducted. Twelve items were found where $p = 0.10$ or better. These items were scored for each S questionnaire (N = 100) and a total MSQ score was related to Dial test performance, yielding a slightly lower but significant correlation (r = 0.41; N = 100; $p < 0.01$). The MSQ scores of 802 students were related to dichotomous criterion of pass/separate. The obtained correlation was very low (r = 0.08) but statistically significant ($p < 0.01$). MSQ scores of an additional 660 students were subjected to an item analysis against a dichotomous criterion of pass/separate. Nine items were found which were each significantly ($p < 0.05$) related to success. These were scored and summed in the MSQs of an	It was shown that an MSQ can be used to predict susceptibility to MS or flight training success.

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					additional validation group and r = 0.24 (N = 660; $p < 0.001$).	
Jones, Levy, Gardner, Marsh, and Patterson	Dec 1985	Airsickness	53 fliers	subjective MS rating, biofeedback-moderated behavioral treatment	Biofeedback-moderated behavioral treatment was provided to 53 fliers grounded for chronic, severe MS. Each S had approximately 20 sessions in the chair, each lasting 30 to 45 minutes twice a day for two work weeks. One session was in the morning and one was in the afternoon. Forty-two fliers (79%) returned to and maintained a satisfactory operational flying status, 3 (6%) were partially successful, and 8 (15%) were grounded for recurrent airsickness.	The failure rate of only 15% attests to the effectiveness of biofeedback-mediated self-regulation to enhance relaxation and to lower autonomic arousal once nausea occurs. Individually tailored elements of biofeed-back, autogenic training, mental imagery, deep muscle relaxation, system desensitization, diaphragmatic breathing, and occasional brief psychotherapeutic interventions enable a chronically airsick flier to control his or her anxiety and to interrupt the autonomic components of early airsickness, thereby allowing continued flight without symptoms progressing to frank, disabling passive or active airsickness.
Johnson and Mayne	1953	airsickness	500	Observations, interviews	Flights in Hadrian gliders and Dakota aircraft. The control group was given a pill (placebo), while the experimental group used headrests. Conditions of turbulence consisted of normal, smooth, rough, and violent. The difference between the proportion of control and experimental groups who became sick in normal turbulence was highly significant ($p < 0.001$), and the difference in each of the rougher conditions is non-significant at the 1% level. For both aircraft types, there is significantly greater incidence of sickness in the control groups at the 1% level. The general conclusion is that the effective-	Headrests have a consistent effect in preventing air MS in Ss during air transportation by Hadrian Glider and Dakota (DC-3) aircraft during all turbulence conditions. It can be predicted that between 60% and 83% of Ss can prevent air MS through the use of a headrest during normal turbulence conditions in the Glider or Dakota aircraft. There is some indication that the incidence of air MS

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					ness of the headrest was demonstrated to be highly significant only in normal turbulence. A surprising conclusion was that the proportion who became sick was independent of past flying experience both for Ss with a headrest and without it. In order to estimate the percentage of susceptible persons prevented from becoming sick by the headrest, 149 persons were taken for two flights each in a Dakota during normal turbulence conditions, first without the headrest, then with the headrest. Of 59 Ss who became sick on the first flight, only 16 were sick on the second. The results concluded that the proportion becoming sick was independent of past flying experience both for Ss with and without the headrest. It was determined that 72.9% (43/59) of susceptible Ss were prevented from becoming air motion sick by the use of the headrests since the proportion of these and similar test Ss who became sick was independent of flying experience. Based on these trials, the 95% confidence interval for the proportion of susceptible Ss who are prevented from becoming airsick is $.60 \leq p \leq .83$. There is some indication that the incidence of air motion sickness in control Ss during normal turbulence decreases as the time since their last meal increases. There was no significant difference between the proportion of experimental or control Ss becoming sick in the Dakota or the Glider flights for any of the turbulence conditions.	decreases as the time since the last meal increases.

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A review of the literature about motion-induced cognitive and perceptual decrements and about motion sickness was conducted to identify screening methods and mitigation techniques and to gain estimates of the portion of population affected. Screening and mitigation techniques that show promise for indirect driving will be evaluated in imminent laboratory and field experiments.

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